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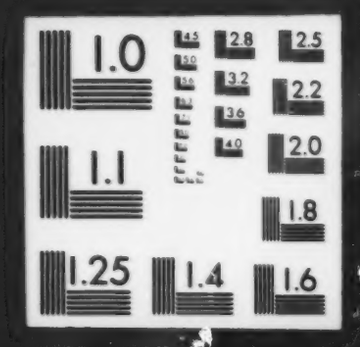

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FLUSHING SMALL SHALLOW LAKES

Claud C. Lomax, et al

Washington State University

Prepared for:

Environmental Protection Agency

December 1971

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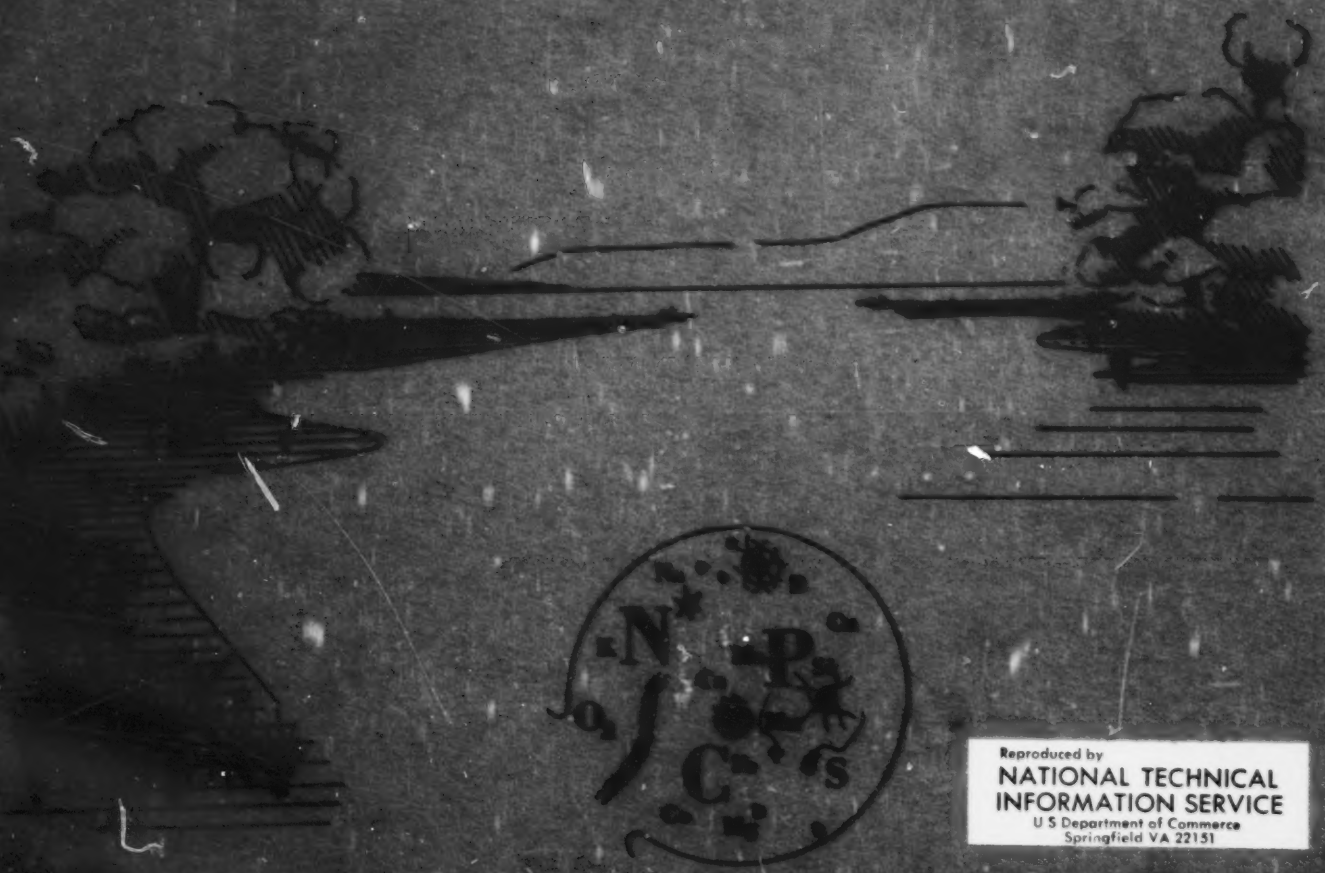

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Flushing of a lake means reducing the pollution by clean inflow with an equivalent outflow of polluted water, a process by which clean water both displaces and mixes with the polluted water. Parameters influencing the effectiveness of the cleansing stream, most important and manageable under laboratory conditions, were investigated. Parameters studied were: inlet velocity, inlet width, depth, and basin shape. Testing was conducted on two depths, two inlet widths, three inlet velocities, and four elliptical basins. Primary purpose of the project was to evaluate the various parameters to determine their influences on flushing efficiency, and develop prediction equations based on geometric and flow characteristics of the systems tested. Analyses were completed to develop a test program, analyze the system for comparison with experimental results, and develop prediction equations which incorporate analytical and experimental results of the study. Width of basin perpendicular to the axis of flow is an important parameter. Narrower basins have better flushing action and less erratic flow patterns than wider basins. Pollution remaining in a basin after any interval of flushing is primarily dependent on the time of the flushing interval divided by the detention time of the basin. (Jones-Wisconsin)

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FLUSHING OF SMALL SHALLOW LAKES

by

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for the
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December 1971

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ABSTRACT

Restoration of quality to polluted lakes by inflows of clean water with simultaneous outflow of polluted water was investigated. Elliptical basins were used in the laboratory to simulate shallow lakes. The investigation determined the influence of selected geometric and flow parameters on the flushing efficiency.

The theoretical analyses are combined with the experimental results to obtain equations for predicting the flushing curves. Application of these equations will give the potential flushing efficiency of a proposed flushing scheme.

The width of the basin perpendicular to the axis of flow is an important parameter. In general, narrower basins have better flushing action and less erratic flow patterns than wider basins. The pollution remaining in a basin after any interval of flushing is primarily dependent on the time of the flushing interval divided by the detention time of the basin.

This report was submitted in fulfillment of Grant Number 16010DMG, under the partial sponsorship of the Water Quality Office, Environmental Protection Agency.

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CONCLUSIONS

1. The most important parameter in determining the shape of the flushing curve, C_R/C_o versus t/t_d, is the variable behavior of the inflow jet.

2. Inlet velocity and depth of flow have no separable effects on the flushing curves.

3. For a predictable jet behavior, the residual concentrations are primarily a function of the time ratio, t/t_d, and the basin shape (aspect ratio, Y/X).

4. The theoretical flushing efficiency as measured by t_s/t_d is influenced directly by the inlet width, W_i, inversely by the aspect ratio, Y/X (Eq. 2).

5. Although the results presented have been derived to apply to flushing pollutants from a lake, the same information can be used to evaluate the degree of increased pollution versus time where a polluted stream (inflow) is permitted to enter a lake.

6. Perhaps the most significant conclusion reached in this study is that a jet entering a shallow basin with a solid boundary (the bottom) and an air-water interface (the free surface), does not follow predicted patterns for a jet discharging into an infinite medium (1). Considerable work remains to be done to describe the behavior of such a jet including the influences of density differentials.

RECOMMENDATIONS

Although this program was conducted under controlled laboratory conditions, valuable information has been developed for planning the enhancement of water quality in polluted lakes situated within reasonable distances of flushing water sources. Factors such as wind and tidal action were not considered in this program, but their relative effects can be relatively estimated. Wind action would tend to promote more complete mixing in shallow lakes, and tidal action would tend to oppose the flushing action. Temperature differentials between the inflow and the lake were not investigated.

Therefore, field pilot studies under natural conditions are an obvious recommendation. Many natural situations of various sizes already exist which could be monitored. Care should be taken to avoid systems which are so large that automatic, continuous monitoring becomes too expensive.

A system analysis study should be conducted, using the results of this study combined with natural physical and climatological factors, to develop an optimum pilot investigation plan. This analysis should be conducted prior to the initiation of any field experiments. Based on the hydraulic and quality parameters of the flow system, the system analysis would be used to determine required sampling location and density, data types and probable scaling factors to be evaluated as a result of different system sizes.

The results of these pilot tests would provide a significant contribution to water resources system design information for the enhancement of quality in polluted lakes as guided by results of this laboratory study.

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INTRODUCTION

Flushing of a lake means reducing the pollution by clean inflow with an equivalent outflow of polluted water. In the process the clean water both displaces and mixes with the polluted water.

Many factors influence the effectiveness of the cleansing stream. This study was conducted to investigate those parameters believed to be most important and manageable under laboratory conditions. The parameters selected for study were: 1) the inlet velocity, 2) the inlet width, 3) the depth, and 4) the basin shape. Testing was conducted on two depths, two inlet widths, three inlet velocities, and four elliptical basins. The primary purpose of the project was to evaluate the various parameters to determine their influences on flushing efficiency, and to develop prediction equations based on the geometric and flow characteristics of the systems tested.

Analyses were completed to: 1) develop a test program, 2) analyze the system for comparison with experimental results, and 3) develop prediction equations which incorporate the analytical and experimental results of the study.

A dimensional analysis of the various geometric, flow, and fluid parameters was completed to isolate the more important variables as a guide for establishing the test program. The average rate of removal of pollutant, $\bar{Q}_r$, was of primary interest and is a varying percent of the inflow rate, Q_i, as a function of time. The following set of dimensionless ratios was developed:

$$f\left[\frac{Q_r}{Q_i}, \frac{W_i^3}{V}, \frac{W_i}{Y}, \frac{W_i}{X}, \frac{W_i}{d}, \frac{Q_i^2\rho}{W_i^2 F_i}, \frac{Q_i\rho}{W_i\mu}\right] = 0. \qquad (1)$$

Terms are defined in Figure 1 and in the Nomenclature. Fluid properties such as density and viscosity were considered constant throughout the system.

Grouping the first four dimensionless terms in Eq. 1 yields an expression for the average rate of soluble pollutant removal during passage of some time, t, such that

$$\bar{Q}_r = K' \frac{W_i^3 X}{dXY \cdot Y} \qquad (2)$$

K' is a dimensionless coefficient containing $4/\pi$ for elliptical basins and is a function of not only the geometric and flow parameters, but also time. K' was found to be independent of the jet momentum force, F_i, and the Reynolds number.

For the general case of flushing lakes for various geometric conditions, Q_r should approach Q_i as W_i approaches Y. Also, as X becomes very

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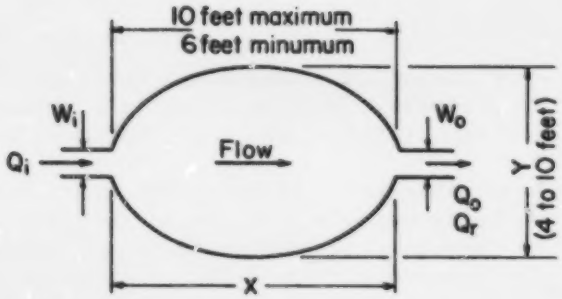
large with respect to W_i and Y, $\overline{Q}_r$ should approach Q_i.

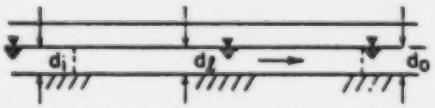
The coefficient K' is used to relate $\overline{Q}_r$ to the actual flushing curve at any relative flushing time, t/t_d, in Figure 2 for a particular lake geometry. An important time ratio for evaluating flushing efficiency is t_s/t_d, or the relative time at which the real flushing curve departs from the ideal flushing curve.

Noting that the volume of the lake is $V = 0.25\pi XYd$ and holding d constant in Eq. 2, it would be expected that as W_i approaches Y, the average rate of pollutant removal $\overline{Q}_r$ approaches Q_i. At the other extreme, W_i approaches zero, Q_i, $\overline{Q}_r$ and the flushing efficiency should all tend towards zero. These general boundary conditions are shown graphically in Figure 3.

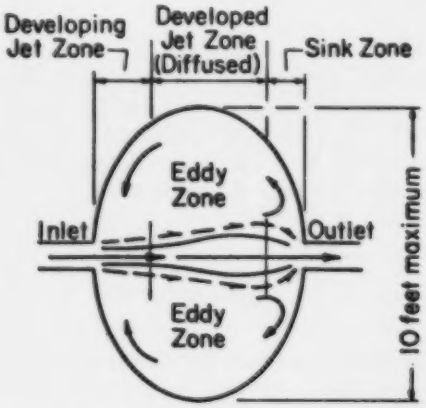
It was found in these tests that for small values of W_i/Y and low inflow discharges, the flushing action can move through the basin as a wave front and be quite efficient. As long as Q_i is finite, the actual flushing curve will follow the ideal flushing curve for a time, t_s/t_d, if external mixing forces such as wind are neglected.



(a) Plan View of a Longitudinal Basin—Hydraulically Long Lake



(b) Elevation, Common to (a) and (c)



(c) Plan View of a Transverse Basin—Hydraulically Short Lake

Fig. 1. Nomenclature and Flow Zone Sketches

A theoretical analysis of the flushing was developed to relate concentration to time. The displacement phase of pollutant removal continues for a time interval, t_s/t_d, with the outflow concentration equal to $C/C_o = 1.0$. The remaining outflow concentration is assumed to follow some form of an exponential expression. Figure 4 shows the assumed curve. The area under the curves to any time, t/t_d, is proportional to the pollutant removed from the basin.

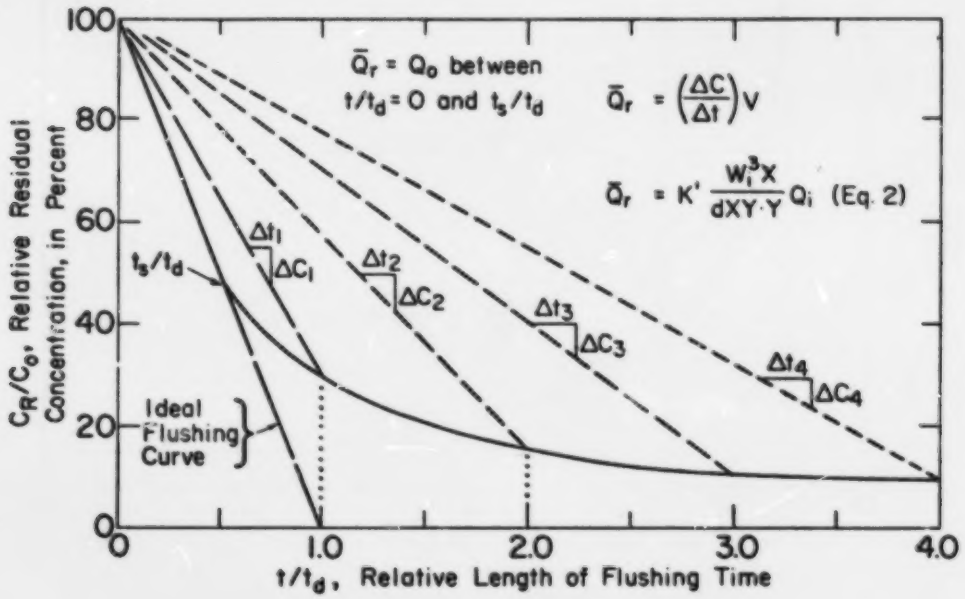


Fig. 2. Residual Concentration and Average Rate of Concentration Removal

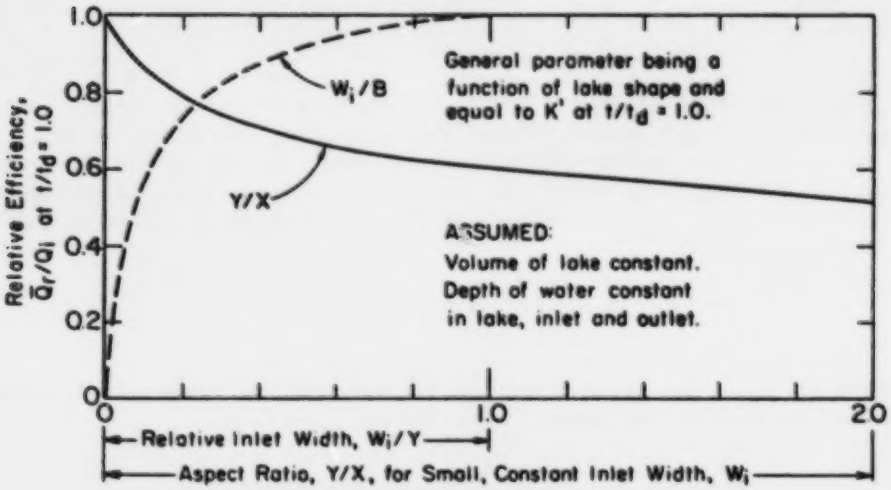


Fig. 3. Generalized Boundary Conditions for Flushing Efficiency

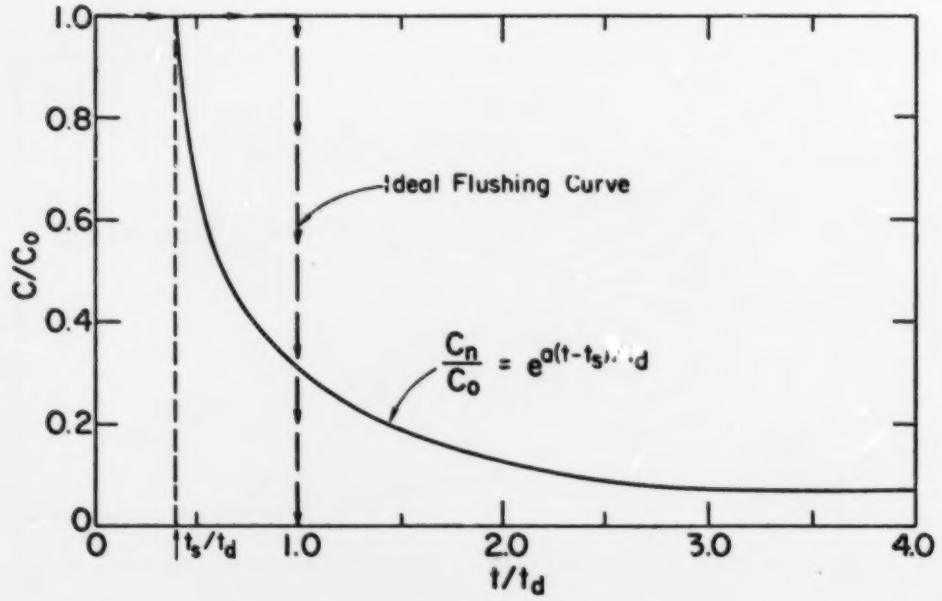


Fig. 4. Smoothed Outflow Concentgraph

The initial quantity of dye in the basin equals 1.0 KV, where K is a dye removal coefficient. The area under the curve from t = 0 to t = ∞ must equal KV. Integrating the equations to find the area and determine "a",

$$KV = Kt_dQ_i \left[\frac{t_s}{t_d} + \int_{t_s/t_d}^{t/t_d=\infty} e^{a(t-t_s)/t_d} \, d\left(\frac{t}{t_d}\right) \right] \tag{3}$$

On the right side of Eq. 3, K is multiplied by t_d to obtain the correct units for new time base. Within the brackets, the first term, t_s/t_d, accounts for area under the horizontal part of the curve; that is, where $C/C_o = 1.0$. The area under the exponential decay part of the curve is determined by $\int_{t_s/t_d}^{\infty}$. Eliminating K and dividing by Q_i to get $V/Q_i = t_d$,

$$\frac{V}{Q_i} = t_d = t_d \left[\frac{t_s}{t_d} + \left| \frac{1}{a} \frac{t_d}{t_d} e^{a(t-t_s)/t_d} \right|_{t_s/t_d}^{\infty} \right] \tag{4}$$

Divide by t_d. The lower limit gives one and the upper limit gives zero for "e" raised to its power. Therefore,

$$1 = \frac{t_s}{t_d} + \frac{1}{a} (+0-1). \tag{5}$$

Solve for

$$a = \frac{-1}{1 - (t_s/t_d)} \tag{6}$$

Residual in Basin = Total at the start minus that removed.

$$K\frac{C_R}{C_o}V = KV - Kt_dQ_i\left[\frac{t_s}{t_d} + \left|\frac{1}{a}e^{a(t-t_s)/t_d}\right|_{t_s/t_d}^{t/t_d}\right] \tag{7}$$

Substitute limits and cancel K. Divide by Q_i to get $t_d = V/Q_i$, and divide by t_d.

$$\frac{C_R}{C_o} = 1 - \left[\frac{t_s}{t_d} + \frac{1}{a}\left(e^{a(t-t_s)/t_d} - 1\right)\right] \tag{8}$$

Now substitute $a = -1/[1-(t_s/t_d)]$ and simplify.

$$\frac{C_R}{C_o} = \left[1 - \frac{t_s}{t_d}\right]\left[e^{-\left(\frac{t}{t_d} - \frac{t_s}{t_d}\right)/\left(1 - \frac{t_s}{t_d}\right)}\right] \tag{9}$$

This equation applies for $t/t_d \geq t_s/t_d$. To obtain C_R/C_o when $t/t_d < t_s/t_d$, use

$$\frac{C_R}{C_o} = 1 - \frac{t}{t_d} \quad . \tag{10}$$

The most significant time ratio in the right side of Eq. 9 is t_s/t_d. Expressing this ratio in terms of the geometric and flow parameters, and inverting to give whole numbers leads to

$$\frac{t_d}{t_s} = \frac{V/Q_i}{X/\bar{v}} \quad . \tag{11}$$

The experimental value of t_s is equal to the X distance divided by the average velocity of the fastest flow-through element. If

$$\bar{v} = bv_i \tag{12}$$

then for elliptical basins, Eq. 11 becomes

$$\frac{t_d}{t_s} = \frac{(\pi/4)(dXY)/Q_i}{X/[Q_i/(bW_id)]} \quad . \tag{13}$$

Eq. 13, when inverted and simplified, gives

$$\frac{t_s}{t_d} = \frac{4bW_i}{\pi Y} \quad . \tag{14}$$

In this form, b can be selected to fit any condition.

It is feasible to assume a value of b for Eq. 14 and compute t_s/t_d and the values of C_R/C_o can then be computed for values of t/t_d using Eq. 9. First the limits will be examined. If $t_s/t_d = 1.0$, then the polluted water is all displaced by the clean inflow and the ideal flushing curve

is followed. Obviously, t_s/t_d cannot exceed 1.0. Assuming instantaneous mixing of the inflow with the basin water, $t_s/t_d = 0$, and the exponential curve starts at $t/t_d = 0$. The assumption of an exponential decay curve implies perfect mixing. This curve and the ideal flushing curve are plotted for Figure 5. It is apparent that any value of t_s/t_d between zero and one will give a curve lying between these two curves.

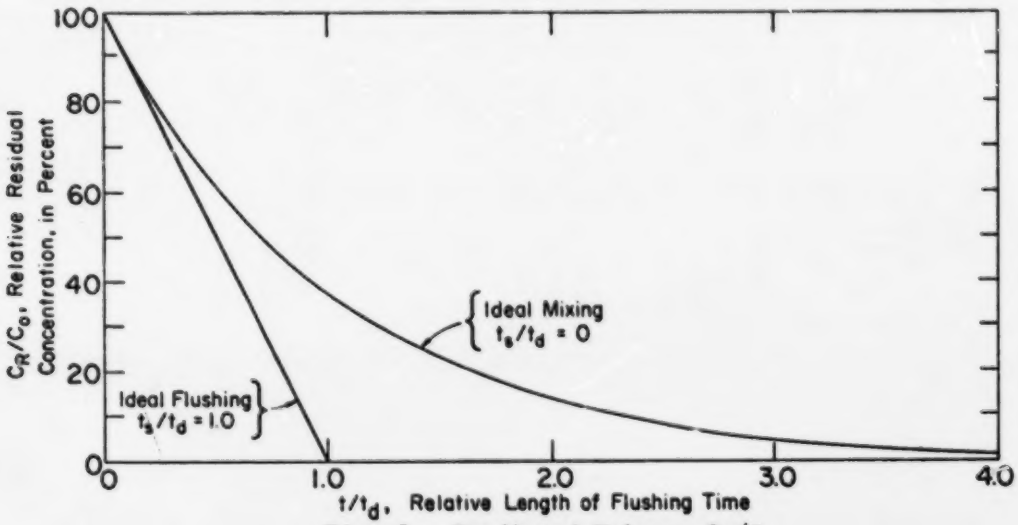


Fig. 5. Predicted Values, C_R/C_o

Table 1 gives the values calculated for predicting C_R/C_o for various t/t_d and t_s/t_d values. Although Table 1 gives valid limits for the assumed conditions, there are other possibilities which are amenable to theoretical analysis. Conditions may change with time so flushing may

Table 1.
Predicted Values, C_R/C_o, from Eqs. 9 and 14

$\frac{t_s}{t_d}$	t/t_d =				
	0	1	2	3	4
(1)	(2)	(3)	(4)	(5)	(6)
0.0	1.0	0.368	0.135	0.050	0.018
0.1	1.0	0.331	0.109	0.036	0.012
0.2	1.0	0.294	0.084	0.024	0.007
0.3	1.0	0.258	0.062	0.015	0.004
0.4	1.0	0.221	0.042	0.008	0.002
0.5	1.0	0.184	0.025	0.003	0.001
0.6	1.0	0.147	0.012	0.001	0.000
0.7	1.0	0.110	0.004	0.000	0.000
0.8	1.0	0.074	0.001	0.000	0.000
0.9	1.0	0.037	0.000	0.000	0.000
1.0	1.0	0.000	0.000	0.000	0.000

be either: 1) displacement, 2) near perfect mixing, or 3) very poor mixing to the extent of clean water short circuiting through the basin to the exit. The experimental values cannot be below the ideal flushing curve in the lower limit curve as given by values in Table 1. Each curve consists of a short section of the ideal flushing curve plus an ideal mixing curve which starts at t_s/t_d. It is recognized that neither ideal mixing nor a perfect short circuit (upper limit of no flushing) are possible. Variability in the experimental values of t_s/t_d can be attributed to: 1) the jet expansion and 2) the type of start, "static" or "running."

Examination of the limits of Eq. 14 reveals some of the complexity of establishing b values. t_d/t_s cannot be less than unity. When $Y/W_i = 1$, $t_d/t_s \simeq 1$ and b must equal $4/\pi$. The minimum value of Y/X also occurs when $Y = W_i$. If $Y = \infty$, then $Y/W_i = \infty$, $t_d = \infty$, and $t_d/t_s = \infty$. However, t_s is finite. If $V_i = 0$, $t_s = 0$, $t_d = \infty$, and $t_d/t_s = \infty$. In this case, Eq. 14 is not valid.

The experimental data have been plotted in Figure 6 to show the dependence of t_d/t_s on aspect ratio Y/X and inlet width W_i. These data are averages for the combined data from two depths and three velocities. Within each group there is random scatter of ±10 percent except for two readings which were ±25 percent from the average. It should be noted that the running start data gave t_d/t_s values which were from two to five times those for the static starts.

The curves shown in Figure 6 can be combined with Eq. 14.

$$\frac{t_d}{t_s} = \frac{8Y}{3W_iX}, \quad (W_i = 4 \text{ in.}) \quad (15)$$

$$\frac{t_d}{t_s} = \frac{10Y}{3W_iX}, \quad (W_i = 8 \text{ in.}) \quad (16)$$

with W_i, X, and Y in feet. In Eqs. 15 and 16, b = 0.29X and 0.24X, respectively, for a typical jet expansion rate.

Considerably more data, preferably under natural conditions, are required to extend with confidence Eq. 15 beyond the limits of these tests.

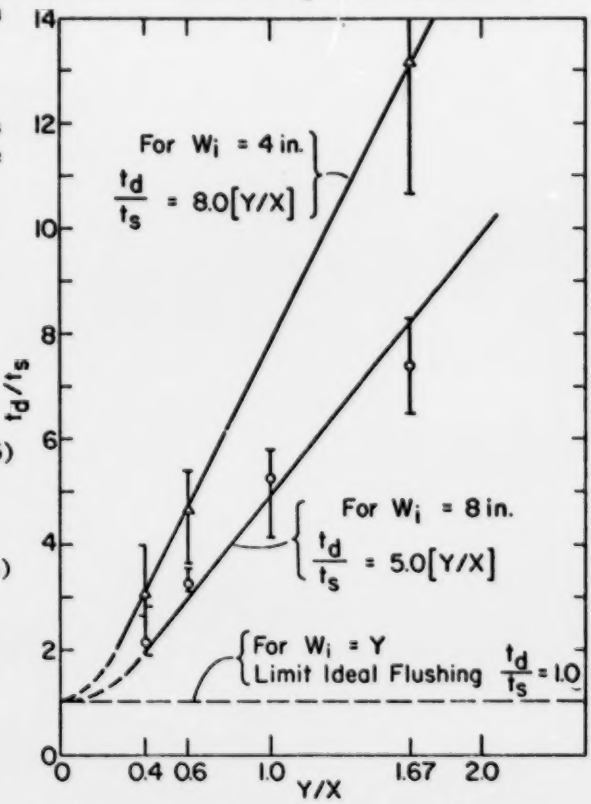


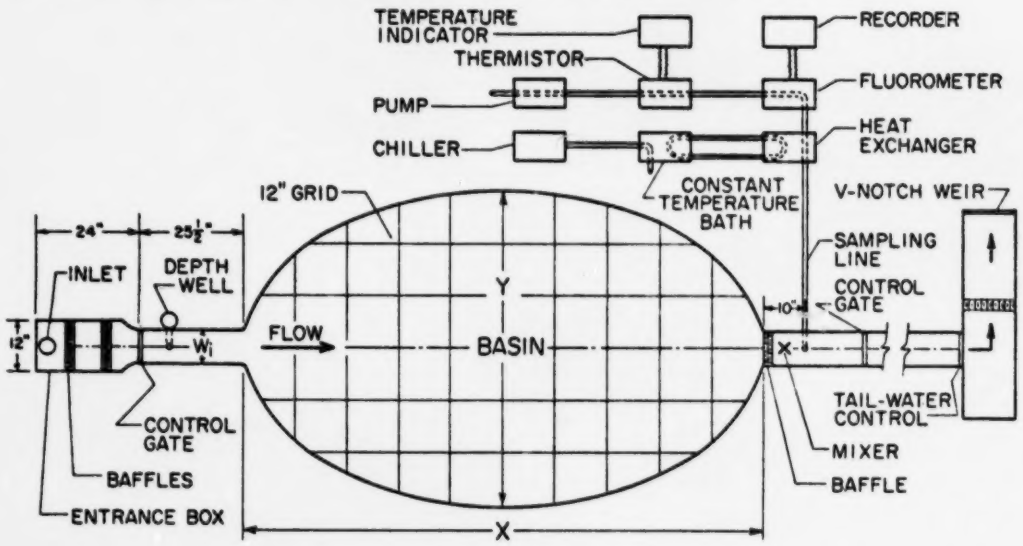
Fig. 6. Flushing Parameter, t_d/t_s, as a Function of Aspect Ratio, Y/X, and Inlet Width, W_i

EXPERIMENTAL APPARATUS

Figure 7 is a schematic of the test apparatus. The test basins were constructed on a 12-foot by 12-foot wood platform. The entrance stilling box, gate, and depth measuring piezometer tap were common for all tests. At the exit, the mixer, Fluorometer tap, control gate, and measuring weir were common. The sides of each basin were fabricated with sheet metal fastened to a plywood template of the desired elliptical shape. The entrance and exit sections were faired to the elliptical basins by a 2-inch radius. Sections were provided for an 8-inch exit width and for both an 8-inch and a 4-inch entrance width for each basin.

A constant head tank supplied the clean water. After the desired flow rate was established with regulating valves, a shut-off valve could be closed and reopened without affecting the flow rate. Flow rates were measured with the 90° V-notch weir. Repeated readings on the point gage established the constancy of flow rate during a test run. A tail-water gate at the exit of the discharge channel controlled the depth. Time-lapse, motion pictures in color were taken at intervals. Rates of one picture per second, per two seconds, or per four seconds were used.

Samples of the outlet channel flow were pumped at a constant rate through a heat exchanger for temperature stabilization, then through the Fluorometer. The Fluorometer readings were recorded with a strip chart recorder. Temperatures were sensed at the outlet of the flow-through door with a thermistor and recorded whenever changes occurred. The inlet and outlet temperatures of the basin were monitored for a few of the final tests. The water in the basin was usually warmer than the inlet supply by 2 to 5 degrees Celsius. The flow was warmed about 1.5 degrees Celsius by heat from the air and lighting during passage through the basin.



PLAN VIEW

Fig. 7. Schematic of Test Apparatus

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TEST PROCEDURE

1. A flow rate was established with the upstream regulating valves.
2. The tailgate was adjusted to establish the desired depth.
3. Flow was shut off without disturbing the regulating valves.
4. The basin was filled to the test depth with water polluted with fluorescent (Rhodamine WT) dye. This dyed water extended to the control gates in the inlet and outlet channels.
5. The entrance box was filled to the necessary depth with clean water.
6. After the basin water became quiescent the upstream control gate was opened.
7. The shutoff valve and the downstream control gate were opened simultaneously.
8. The Fluorometer, timing, and camera systems were started with the start of flow into the entrance channel.

At the beginning of each test the basin concentration was adjusted to be within the range 85 to 100 percent on the Fluorometer scale being used. The test was terminated when the outflow percentage reached about five percent. Table 2 summarizes the parameters studied in this investigation.

Table 2. Summary of Test Conditions

Variable	Basin Size, in feet, Y by X			
	4 by 10	6 by 10	10 by 10	10 by 6
(1)	(2)	(3)	(4)	(5)
Inlet width, in inches	4.0	4.0		4.0
	8.0	8.0	8.0	8.0
Inlet velocity, in feet per second	0.1	0.1	0.1	0.1
	0.2	0.2	0.2	0.2
	0.4	0.4	0.4	0.4
Depth, in inches	2.0	2.0	2.0	2.0
	4.0	4.0	4.0	4.0
Running Start also tested	No	Yes	No	No

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DATA ANALYSIS

The raw data from the strip charts were corrected for temperature variations in the sample temperature by the technique given by Cobb and Bailey (2). Time adjustments were made to correct the raw data for transit time in the inlet, and the delay due to passage through the outlet channel and the tube leading to the Fluorometer. Although a small error exists due to instrument response lag, no correction was made for it.

In Figure 8 the data were reduced to a common comparison base by using the relative concentration; that is, measured concentration divided by initial concentration and multiplied by 100 to return to percentages. A dimensionless time equal to the time from the start of flushing (when clean water enters the basin) divided by the basin detention time has also been used for all comparisons and evaluations. Figure 8 may be thought of as a dimensionless hydrograph of the outflow concentration.

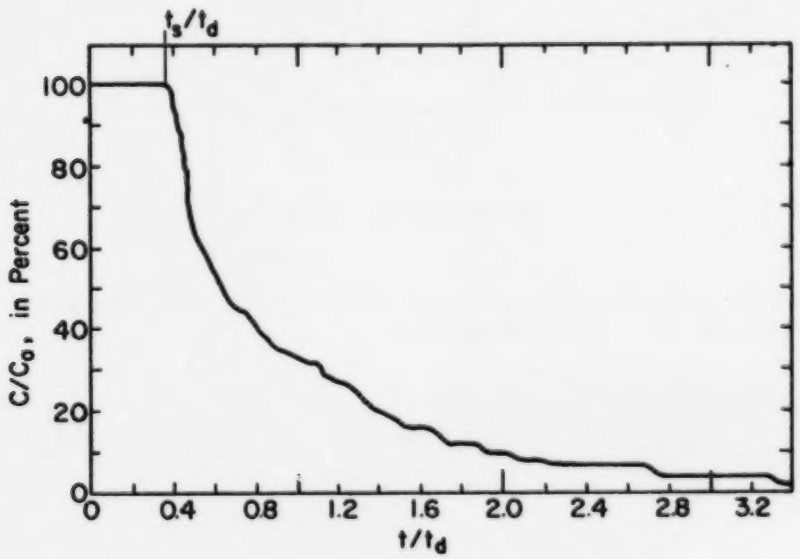

Fig. 8. Typical Outflow Hydrograph, C/C_o Versus t/t_d

The area under the curve when multiplied by the proper factors gives the quantity of dye removed. This subtracted from the initial quantity gives the residual concentration. Considerable local variation from this average value will occur throughout the basin.

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Referring to the simplified concentration versus time curve in Figure 9:

$$\text{Initial quantity of dye} = KC_oV \tag{17}$$

$$\text{Dye removed} = K\int_{t_o}^{t_n} Q_i C_n dt \tag{18}$$

$$\text{Residual quantity of dye} = KC_RV = K(C_RV - \int_{t_o}^{t_n} Q_i C_n dt) \tag{19}$$

$$\text{Basin volume} = V = 0.25\,\pi XYd \tag{20}$$

$$\text{Basin detention time} = t_d = \frac{V}{Q_i} = \frac{0.25\pi XYd}{Q_i} \tag{21}$$

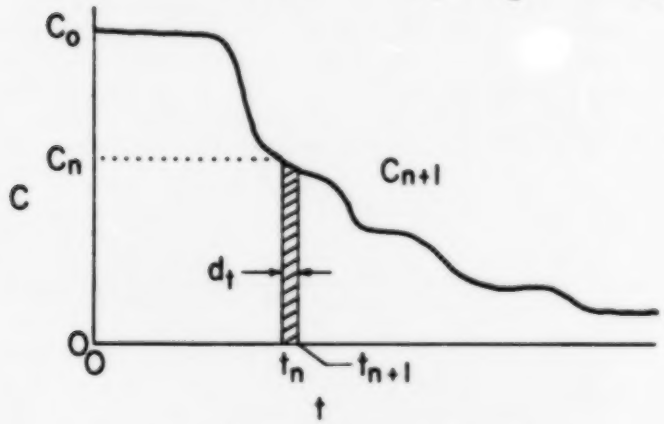

Fig. 9. Concentration Versus Time

Eliminate K, substitute $Q_i t_d$ for V, divide by C_o and introduce t_d into the third term of Eq. 19 to obtain:

$$\left[\frac{C_R}{C_o}\right] Q_i t_d = \left[\frac{C_o}{C_o}\right] Q_i t_d - Q_i t_d \int_{t_o/t_d}^{t_n/t_d} \left[\frac{C_n}{C_o}\right] d\left(\frac{t}{t_d}\right) \tag{22}$$

Simplify to:

$$\frac{C_R}{C_o} = 1 - \int_{t_o/t_d}^{t_n/t_d} \left[\frac{C_n}{C_o}\right] d\left(\frac{t}{t_d}\right) \tag{23}$$

When multiplying by 100 to get the relative concentration on a percentage basis, Eq. 23 is applicable to the curve shown in Figure 8.

Because the experimental C_n versus t curve is not mathematically definable, discrete steps as shown in Figure 9 must be summed to obtain the area under the curve. Equation 24 shows this summation as it was used in the computer program to obtain the relative residual concentration, C_R/C_o.

$$\left(\frac{C_R}{C_o}\right)100 = \left\{1 - 0.5 \sum_{t_o}^{t_{n+1}} \left[\frac{(C_{n+1} + C_n)}{C_o}\right]\left[\frac{(t_{n+1} - t_n)}{t_d}\right]\right\}100 \qquad (24)$$

The required time and temperature corrections were applied to the data read from the strip chart before they were entered into a program on the GE 235. Table 3 is a printout from this program. The first two columns are the inputs of time and fluorescence concentration in the outflow. The third column shows the relative fluorescence of the outflow, $(100C/C_o)$. The fourth column gives the ratio of time to detention time, and the last column shows the mean residual relative concentration in the basin, $(100C_R/C_o)$.

The residual concentration calculated for the terminal time can be compared with the residual measured with the Fluorometer after thoroughly mixing the basin contents at the end of the test. The measured value was four percent and the calculated value was one percent for this example.

Table 3. Data and Computed Values

t, in seconds (1)	C, in percent (2)	C/C_o (3)	t/t_d (4)	C_R/C_o (5)	t, in seconds (1)	C, in percent (2)	C/C_o (3)	t/t_d (4)	C_R/C_o (5)
.	94.	100.	.00	100.	648.	38.	40.	.88	53.
68.	94.	100.	.09	91.	660.	36.	38.	.90	52.
77.	92.	98.	.10	90.	691.	34.	36.	.94	50.
79.	90.	96.	.11	89.	725.	32.	34.	.98	49.
82.	88.	94.	.11	89.	743.	30.	32.	1.01	48.
85.	86.	91.	.12	89.	767.	30.	32.	1.04	47.
88.	84.	89.	.12	88.	814.	28.	30.	1.10	45.
90.	82.	87.	.12	88.	855.	28.	30.	1.16	43.
95.	80.	85.	.13	87.	910.	26.	28.	1.23	41.
98.	78.	83.	.13	87.	960.	26.	28.	1.30	39.
101.	76.	81.	.14	87.	980.	24.	26.	1.33	39.
103.	74.	79.	.14	86.	1008.	24.	26.	1.37	38.
105.	72.	77.	.14	86.	1071.	22.	23.	1.45	35.
106.	70.	74.	.14	86.	1160.	22.	23.	1.57	33.
108.	68.	72.	.15	86.	1182.	20.	21.	1.60	32.
110.	66.	70.	.15	86.	1304.	20.	21.	1.77	28.
112.	64.	68.	.15	86.	1312.	18.	19.	1.78	28.
113.	62.	66.	.15	85.	1427.	16.	17.	1.94	25.
115.	60.	64.	.16	85.	1481.	16.	17.	2.01	24.
118.	58.	62.	.16	85.	1555.	14.	15.	2.11	23.
120.	56.	60.	.16	85.	1602.	14.	15.	2.17	22.
122.	54.	57.	.17	85.	1638.	12.	13.	2.22	21.
126.	52.	55.	.17	84.	1713.	12.	13.	2.32	20.
131.	50.	53.	.18	84.	1780.	10.	11.	2.42	19.
166.	50.	53.	.23	82.	1955.	10.	11.	2.65	16.
182.	48.	51.	.25	80.	2004.	8.	9.	2.72	15.
200.	46.	49.	.27	79.	2266.	8.	9.	3.07	12.
240.	44.	47.	.33	77.	2340.	6.	6.	3.18	12.
348.	44.	47.	.47	70.	2677.	6.	6.	3.63	9.
368.	42.	45.	.50	68.	2837.	4.	4.	3.85	8.
434.	42.	45.	.59	64.	2965.	4.	4.	4.02	7.
469.	40.	43.	.64	62.	3000.	3.	3.	4.07	7.
478.	38.	40.	.65	62.	3305.	3.	3.	4.48	5.

TEST RESULTS

The computed values for each run were plotted and the smooth curves shown in Figures 10 through 13 were drawn. The solid line was drawn through the visual average of the data. The dashed lines show the range for two identical runs having the greatest spread, and the dotted lines border the inclusive field for all data taken on the basin.

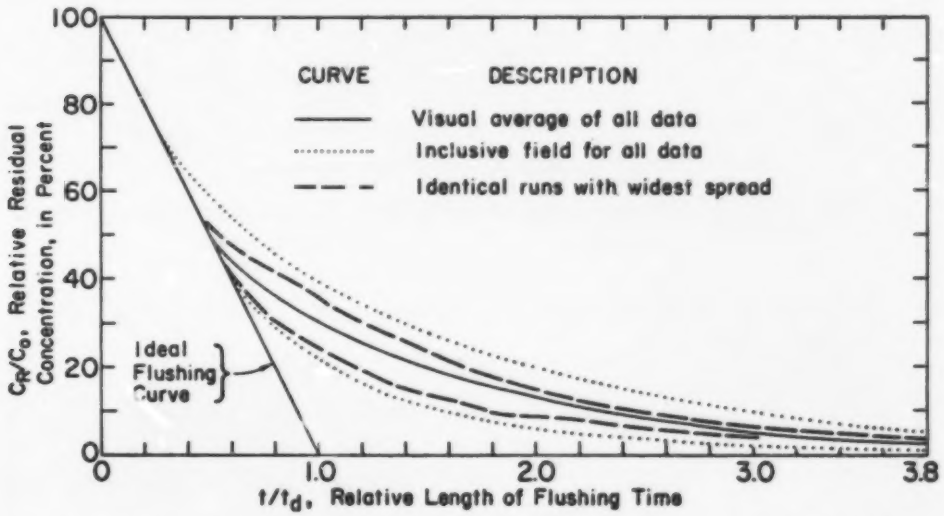

Fig. 10. Flushing Curves for 10-Foot by 4-Foot Basin (X·Y)

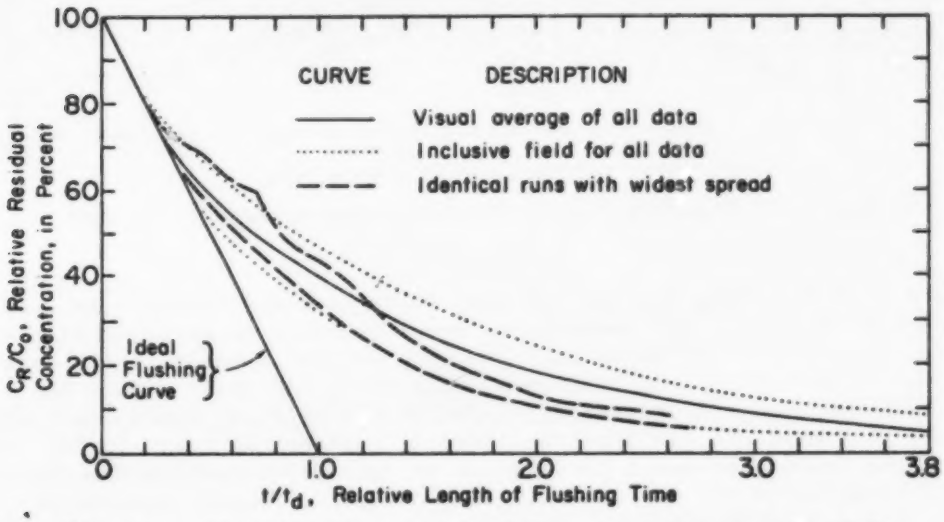

Fig. 11. Flushing Curves for 10-Foot by 6-Foot Basin (X·Y)

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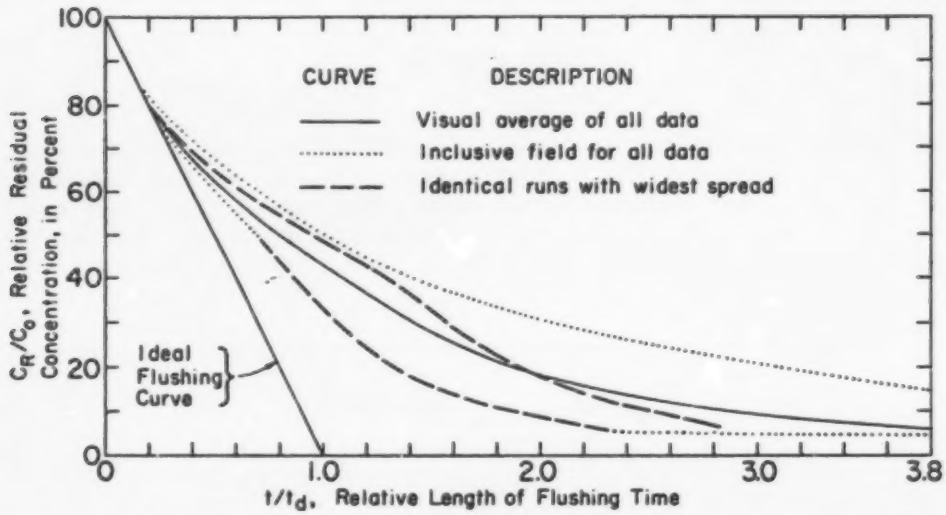

Fig. 12. Flushing Curves for 10-Foot by 10-Foot Basin (X·Y)

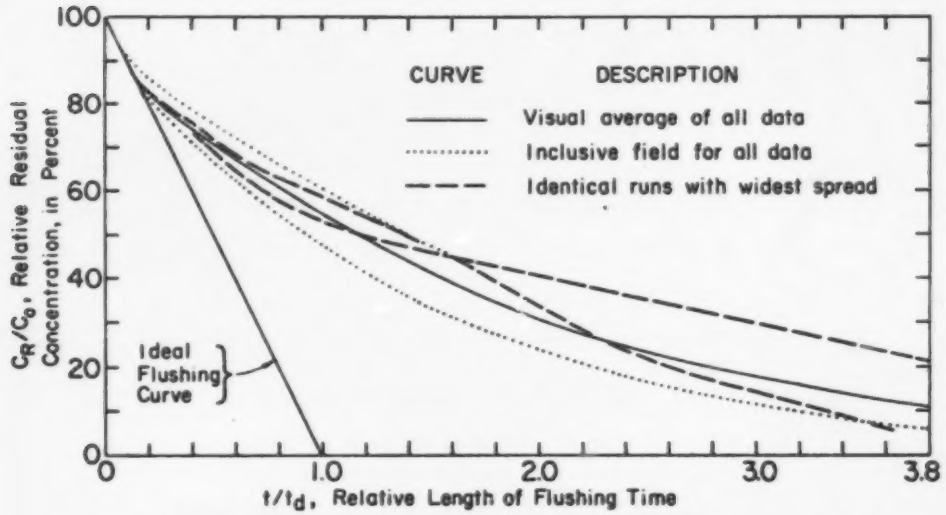

Fig. 13. Flushing Curves for 6-Foot by 10-Foot Basin (X·Y)

Most of the testing was done by introducing a clean stream into a polluted static basin and removing an equal quantity of polluted flow at the opposite end of the basin. However, several running starts were made. Flow through the basin was established and dye fed into the inflow. When the concentrations of dye in the outflow, basin, and inflow were the same, the dye feed was stopped to start the run. During the running starts the basin circulation pattern was established by the time the clean water was introduced. Therefore, the transit time across the basin was much shorter and, consequently, the initial flushing was less efficient for the running starts than for the static starts. The time required to reach a C_R/C_o value of five percent was essentially the same for both types of starting.

With a data spread for identical conditions nearly as great as the inclusive field for all tests of a basin, the effect of the test parameters is either completely masked or barely discernible.

Motion pictures of identical conditions show completely different jet behavior. Selected frames from the motion pictures do not show the complete jet action and the dispersion with time but they do indicate stages of the dispersion and jet movement and permit comparisons to be made. Figure 14 shows the persistence of "hot" islands of pollutant for Run I that do not occur in identical Run II.

In the first run of another test, the inflow jet spread laterally almost across the basin, mixed with the dye, and swept the pollution toward the outlets in a "front." In an identical run the inflow jet remained isolated and mixed only at the edges so that a clean or slightly mixed stream penetrated to the outlet. Whether such jet behavior is a random phenomena or is triggered by subtle differences in the test conditions remains to be determined.

DISCUSSION OF TEST RESULTS

Two distinct yet related flushing actions take place. Initially, the clean water displaces polluted water and this is the most efficient flushing possible. In fact, if a barrier could isolate the clean water from the polluted water and prevent mixing as the jet spread laterally, the basin would be cleansed in a time, $t/t_d = 1.0$. Figures 10 through 13 show this ideal flushing curve as a straight line between $C_R/C_o = 100$, $t/t_d = 0.0$; and $C_R/C_o = 0.0$, $t/t_d = 1.0$. The efficiency of the flushing can be judged by how close the experimental curve comes to this ideal curve.

However, mixing does occur and this modifies the flushing curve. Ideally, the incoming water should spread across the basin and mix uniformly at the front. This would accomplish two desirable objectives: 1) the time of the displacement phase would be long, and 2) there would be no isolated islands of highly polluted water left in the basin.

Figure 15 shows the strong demarcation that occurs between the original basin water and the inflow when the jet diffuses across the basin laterally. This run had a long initial displacement time, t_s/t_d.

Figure 16 shows a reproduction of the average curves for the basins studied. The wider the basin, the greater the relative time, t/t_d, required to reach a given relative residual concentration. The time during which the flushing curve coincides with the ideal flushing curve is inversely proportional to the width of the basin.

Run I

Run II

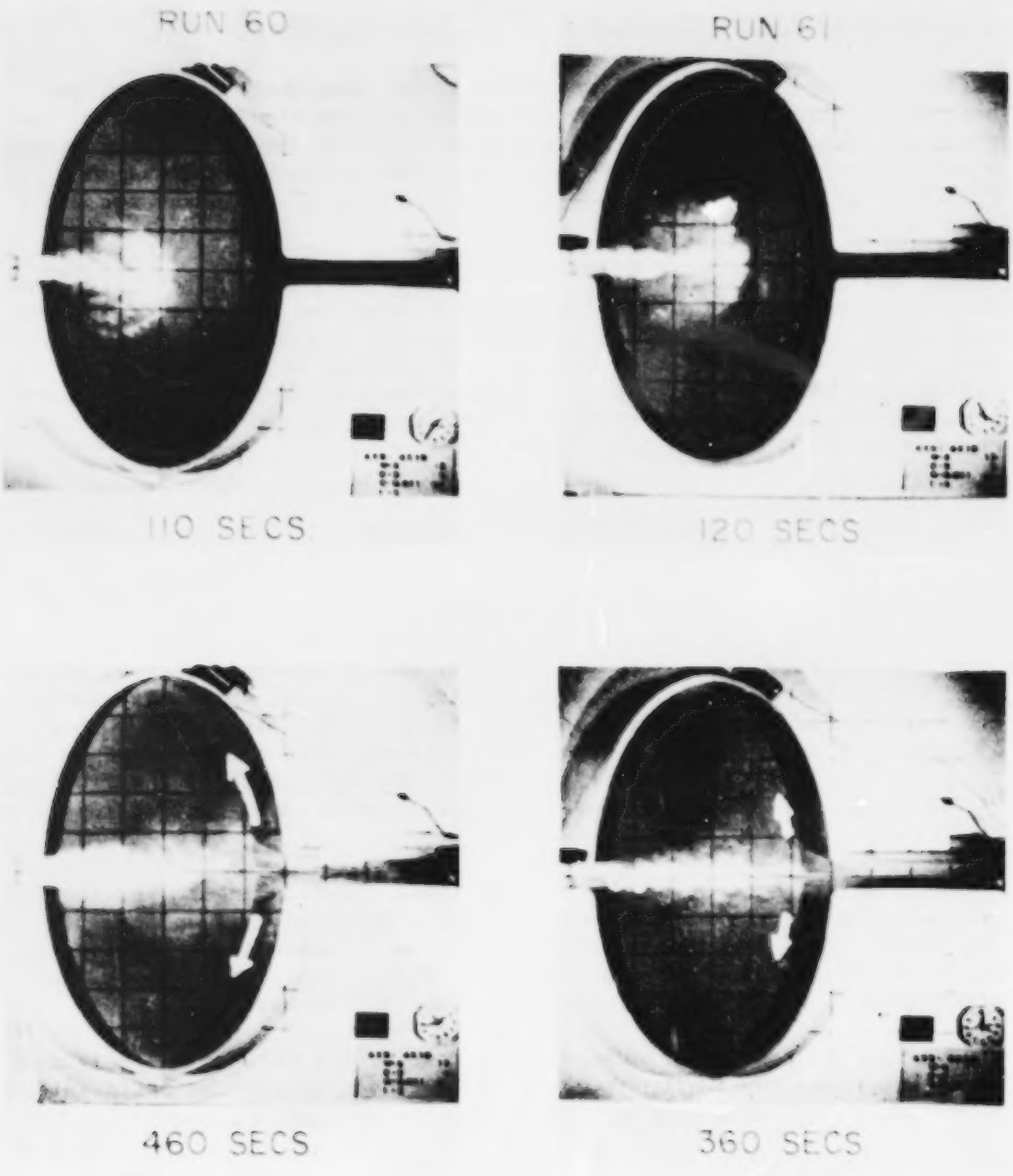

Fig. 14. Identical Run Comparison, Runs 60 and 61

X by Y = 6 ft by 10 ft,
W_i = 8 in., d = 2 in., v = 0.1 fps.
Note dye islands in Run I.
Arrows indicate circulation

Run I

Run II

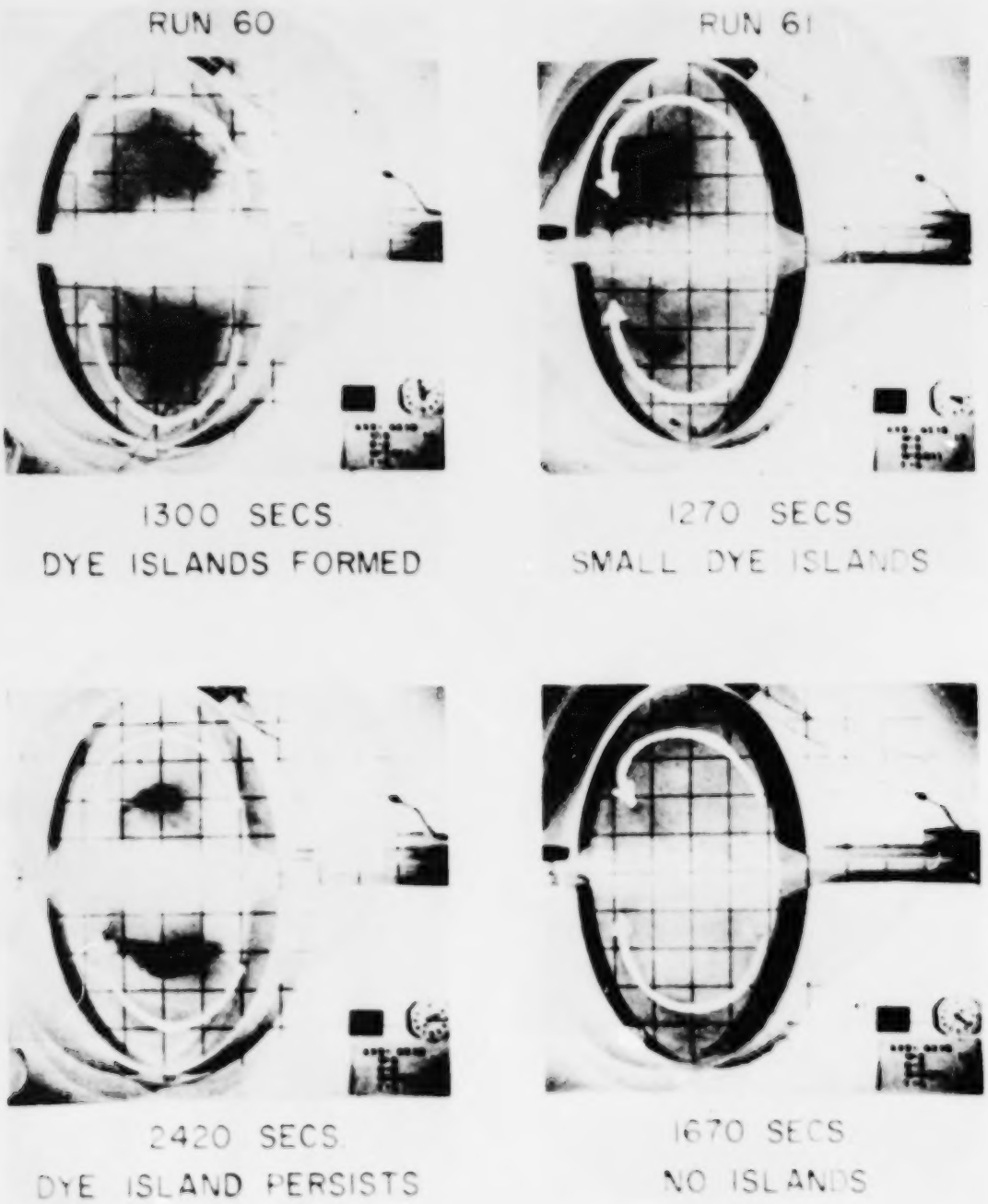

Fig. 14. (continued)

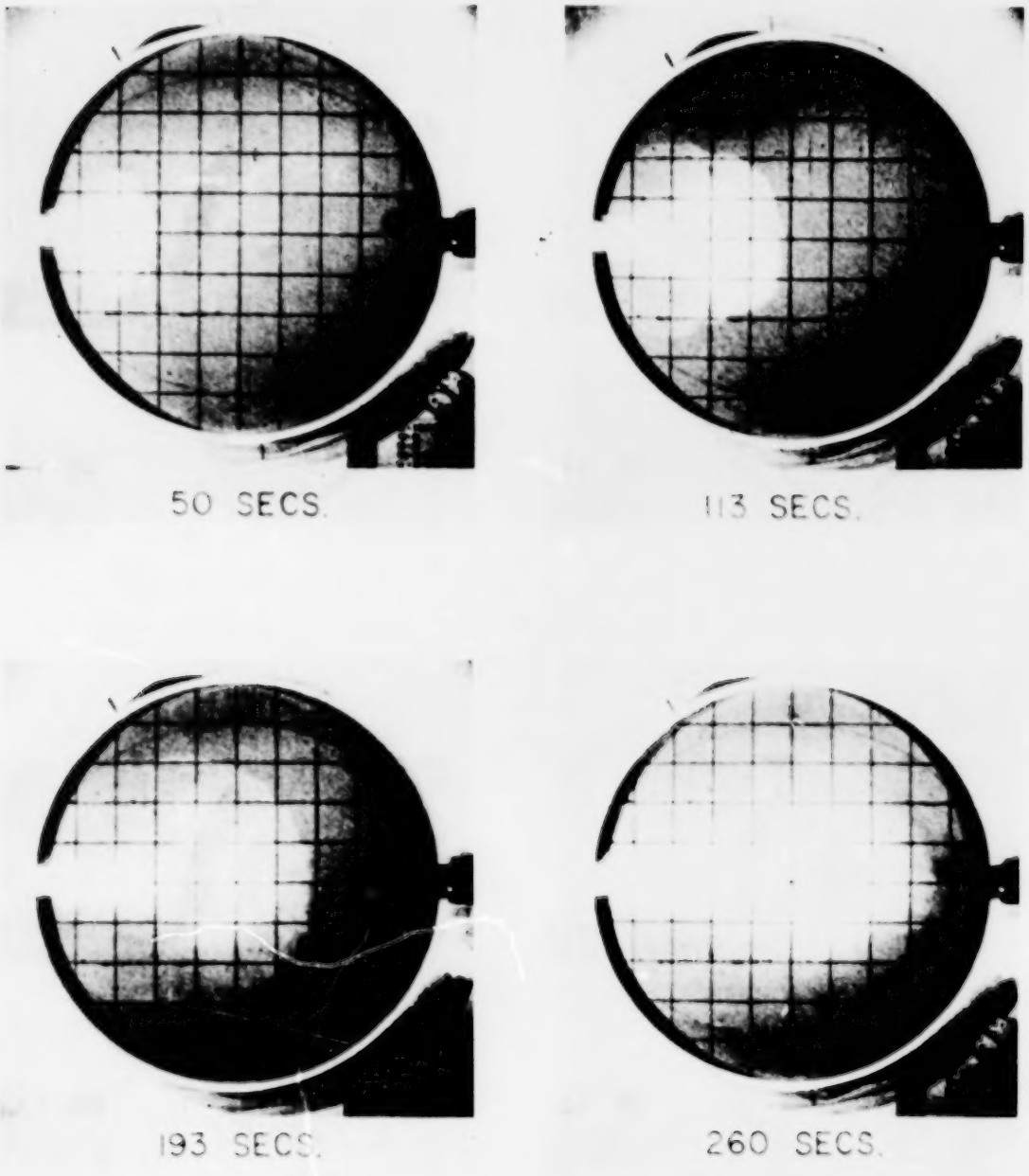

Fig. 15. Example of Well-Diffused Jet

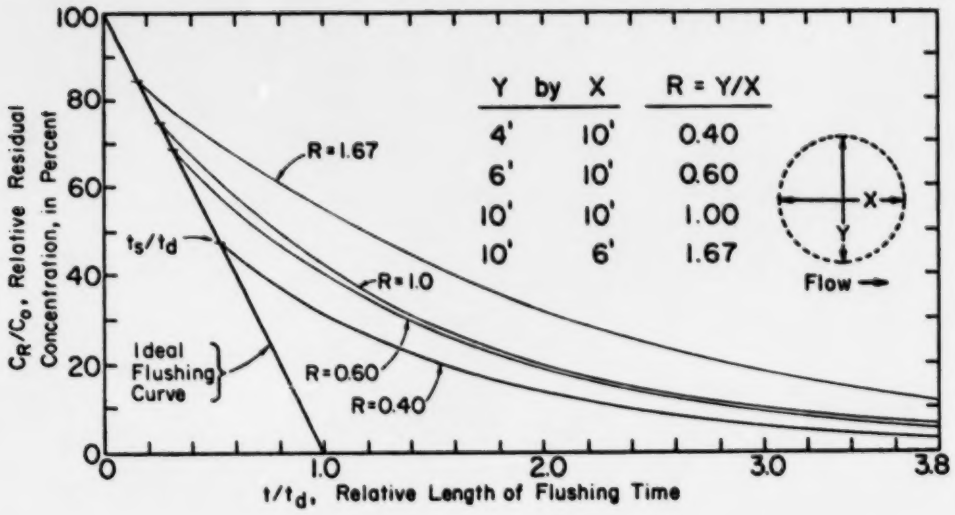

Fig. 16. Comparison of Average Flushing Curves

ACKNOWLEDGMENTS

The co-investigators on this project were Claud C. Lomax and John F. Orsborn. A significant contribution to the analysis and data reduction was made by S. T. Chen and C. Y. Eric Shih, Research Assistants in the Albrook Hydraulic Laboratory. This study was performed under Grant 16010 DMG by the Federal Water Quality Administration with grantee contributions by the College of Engineering Research Division of Washington State University, Pullman, Washington. The Project Officer was Charles F. Powers, Pacific Northwest Water Laboratory, Water Quality Office, Environmental Protection Agency, Corvallis, Oregon.

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APPENDICES

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APPENDIX A. NOTATION

The following symbols are used in this paper:

a	coefficient in exponential equation
b	coefficient for ratio of transit velocity to inlet velocity
C	concentration, in percent
C_n	outflow concentration at time, t_n, in percent
C_o	initial concentration in the basin, in percent
C_R	residual concentration in the basin, in percent
d	depth of flow or depth of lake, in feet
e	2.718
f	function of
F_i	momentum force in inflow, in pounds
K	coefficient used to obtain the absolute amount of dye removed from the concentration measured, in percent
K'	general pollutant removal coefficient used in Eq. 4
Q_e	flow entrained by jet
Q_i	inflow rate, in cubic feet per second (Q_o)
Q_o	outflow rate, cubic feet per second
Q_r	removal rate, in cubic feet per second
$\overline{Q}_r$	average removal rate, cubic feet per second
Q_t	$Q_i + Q_e$, in cubic feet per second
R	aspect ratio
t	time, in seconds
t_d	basin detention time = V/Q_i, in seconds
t_n	time measured from start of clean flow into basin, in seconds
t_o	time zero

t_s basin transmit time (time from the start of clean flow into basin until the outflow concentration shows its effect in that C_n is less than C_o), in seconds

$\bar{v}$ mean basin flow through velocity = $v_i/2$, in feet per second

v_e entrainment velocity, in feet per second

v_i velocity in the inflow channel, in feet per second

V volume of basin, in cubic feet

W_i width in inlet, in feet

W_o width in outlet, in feet

X length of ellipse parallel to the direction of flow, in feet

Y width of ellipse perpendicular to the direction of flow, in feet

ΔC change in concentration in time integral Δt

Δt time integral

μ absolute viscosity of liquid, assumed constant, in pound-second per square foot

ρ mass density of liquid, assumed constant for inflow and lake, in slugs per cubic foot

Table 4.

Data Summary for 10-Foot by 4-Foot Basin

In order of Hour-Day-Month-Year	Run Number	X, in feet	Y, in feet	W_i, in inches	d, in inches	v, in feet per second	Q_i, in cubic feet per second	t_s, in seconds	t_d, in seconds	Relative Residual Concentration, C_R/C_o, in percent					
										Terminal		At t/t_d =			
										Measured	Calculated	2.5	3.0	3.5	4.0
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1420-16-5-69	22	10	4	8	2	0.1	0.011	202	472	2	2	3	2*	1*	1*
1555-16-5-69	23	10	4	8	2	0.1	0.011	242	458**	4	4	3*	2*	1*	1*
0850-20-5-69	24	10	4	8	2	0.2	0.022	93	224**	3	3	10	6	4	3*
0950-20-5-69	25	10	4	8	2	0.2	0.022	100	222**	4	4	11	8	5	3*
0855-27-5-69	26	10	4	8	2	0.4	0.040	60	130	2	1	9	6	3	2
1000-27-5-69	27	10	4	8	2	0.4	0.040	61	134**	3	3	10	7	6	5
0910-4-6-69	28	10	4	8	4	0.2	0.044	110	250**	2	2	5	3	2*	1*
1545-4-6-69	29	10	4	8	4	0.2	0.044	120	250**	1	1	5	3	2	1
1315-6-6-69	30	10	4	8	4	0.2	0.044	124	236**	1	1	5	3	1	1*
1530-6-6-69	31	10	4	8	4	0.2	0.044	103	236**	2	2	9	6	4	3
1555-9-6-69	32	10	4	8	4	0.2	0.044	77	221**	2	2	7	4	3	1*
1135-10-6-69	33	10	4	8	2	0.2	0.022	109	225**	2	3	6	4	2*	1*
1400-10-6-69	34	10	4	8	2	0.2	0.022	105	221**	3	3	5	4	2*	1*
1145-13-6-69	35	10	4	4	2	0.4	0.022	65	262**	4	4	14	10	6	5
1350-13-6-69	36	10	4	4	2	0.4	0.022	74	247	3	4	13	9	6	4
1445-17-6-69	37	10	4	4	2	0.1	0.0056	345	828	3	2	6	3	2*	1*
1613-17-6-69	38	10	4	4	2	0.1	0.0056	310	828	4	3	7	4	3*	2*
										Maximum		14	10	6	5
										Minimum		3	2	1	1
										Average		8	5	3	2
										Spread		11	8	5	4

*Extrapolated

**Adjusted

Table 5.

Data Summary for 10-Foot by 6-Foot Basin

In order of Hour-Day-Month-Year	Run Number	X, in feet	Y, in feet	W_i, in inches	d, in inches	v, in feet per second	Q_i, in cubic feet per second	t_s, in seconds	t_d, in seconds	Relative Residual Concentration, C_R/C_o, in percent					
										Terminal		At t/t_d =			
										Measured	Calculated	2.5	3.0	3.5	4.0
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1030-5-8-69	39	10	6	8	2	0.2	0.0222	107	342	7	2	16	12	9	7
1500-5-8-69	40	10	6	8	2	0.2	0.0222	99	342	6	2	18	14	11	8
1445-6-8-69	41	10	6	8	2	0.2	0.0222	39**	342	5	6	18	14	11	8
0845-12-8-69	42	10	6	8	2	0.1	0.0111	220	722	5	7	10	7	4*	3*
1115-12-8-69	43	10	6	8	2	0.1	0.0111	200	722	6	5	8	5	3*	2*
1345-12-8-69	44	10	6	8	2	0.1	0.0111	58**	722	4	4	10	7	4	3*
1600-14-8-69	45	10	6	8	2	0.4	0.0444	55	176	4	2	11	7	4	3
0900-15-8-69	46	10	6	8	2	0.4	0.0444	55	176	2	1	13	9	6	3
1030-15-8-69	47	10	6	8	2	0.4	0.0444	27**	176	5	4	20	15	11	8
1340-15-8-69	48	10	6	8	4	0.2	0.0444	111	352	3	9	13	11	9	6*
1445-15-8-69	49	10	6	8	4	0.2	0.0444	66**	352	4	7	20	14	10	8
1000-2-9-69	50	10	6	4	2	0.4	0.0222	77	381	5	3	12	9	5	3
1130-2-9-69	51	10	6	4	2	0.4	0.0222	77	381	7	5	13	9	5	2*
1430-2-9-69	52	10	6	4	2	0.4	0.0222	20**	402	4	1	13	8	5	2
1600-3-9-69	53	10	6	4	2	0.4	0.0222	72	402	4	5	13	8	6	2*
1045-4-9-69	54	10	6	4	4	0.2	0.0222	217	804	8	5	11	7	4*	3*
1420-4-9-69	55	10	6	4	4	0.2	0.0222	159	804	5	0	13	8	5	3
0900-5-9-69	56	10	6	4	2	0.2	0.0111	145	701	5	5	15	10	6	3*
1125-5-9-69	57	10	6	4	2	0.2	0.0111	150	701	6	6	13	8	5*	2*
1020-8-9-69	58	10	6	4	2	0.1	0.0055	405	1512	5	6	7	4*	3*	2*
1355-8-9-69	59	10	6	4	2	0.1	0.0055	335	1676	5	6	9	6*	4*	3*
										Maximum		20	15	11	8
										Minimum		7	4	3	2
										Average		13	9	6	4
										Spread		13	11	8	6

*Extrapolated

**Running Start

Table 6.

Data Summary for 10-Foot by 10-Foot Basin

In order of Hour-Day-Month-Year (1)	Run Number (2)	X, in feet (3)	Y, in feet (4)	W_i, in inches (5)	d, in inches (6)	v, in feet per second (7)	Q_i, in cubic feet per second (8)	t_s, in seconds (9)	t_d, in seconds (10)	Relative Residual Concentration, C_R/C_o, in percent					
										Terminal		At t/t_d =			
										Measured (11)	Calculated (12)	2.5 (13)	3.0 (14)	3.5 (15)	4.0 (16)
1100-26-3-69	11	10	10	8	2	0.4	0.0388	58	330**	7	8	17	13	9	8*
1000-1-4-69	12	10	10	8	2	0.4	0.0444	50	278**	8	9	17	12	9	8*
0915-2-4-69	13	10	10	8	4	0.2	0.0444	103	484**	3	3	13	9	6	5
1415-3-4-69	14	10	10	8	2	0.2	0.0222	102	572**	6	6	10	7	5*	4*
1045-4-4-69	15	10	10	8	2	0.2	0.0222	106	590	6	6	10	7	5*	4*
1040-11-4-69	16	10	10	8	2	0.1	0.0111	310	1298**	7	6	5	4	3*	2*
1435-14-4-69	17	10	10	8	2	0.1	0.0111	217	1263**	8	7	10	7*	6*	5*
1030-16-4-69	18	10	10	8	2	0.1	0.0111	218	1274**	6	5	7	5*	4*	3*
1040-18-4-69	19	10	10	8	4	0.1	0.0222	213	1133**	11	11	13	10*	8*	7*
1450-18-4-69	20	10	10	8	4	0.1	0.0222	244	1180	9	8	14	10	8*	7*
1030-25-4-69	21	10	10	8	4	0.2	0.0444	105	590	12	11	25	21	16	14
										Maximum		25	21	16	14
										Minimum		5	4	3	2
										Average		13	10	7	6
										Spread		20	17	13	12

*Extrapolated

**Adjusted

Table 7.

Data Summary for 6-Foot by 10-Foot Basin

In order of Hour-Day Month-Year (1)	Run Number (2)	X, in feet (3)	Y, in feet (4)	W_i, in inches (5)	d, in inches (6)	v, in feet per second (7)	Q_i, in cubic feet per second (8)	t_s, in seconds (9)	t_d, in seconds (10)	Relative Residual Concentration, C_R/C_o, in percent					
										Terminal		At t/t_d =			
										Measured (11)	Calculated (12)	2.5 (13)	3.0 (14)	3.5 (15)	4.0 (16)
1335-15-9-69	60	6	10	8	2	0.1	0.0111	82	687	7	8	34	29	27	26
1555-15-9-69	61	6	10	8	2	0.1	0.0111	90	687	6	1	21	14	8	5
1600-16-9-69	62	6	10	8	2	0.2	0.0222	47	342	4	2	19	13	9	7
0945-17-9-69	63	6	10	8	2	0.2	0.0222	48	342	2	1	27	20	15	11
1320-17-9-69	64	6	10	8	2	0.2	0.0222	47	342	6	1	23	17	11	8
0930-18-9-69	65	6	10	8	2	0.4	0.0444	24	178	4	1	27	22	17	13
1135-18-9-69	66	6	10	8	2	0.4	0.0444	25	178	9	3	28	22	17	13
0846-19-9-69	67	6	10	8	4	0.2	0.0222	43	356	6	8	20	16	13	11
1129-19-9-69	68	6	10	8	4	0.2	0.0222	54	356	7	7	20	17	12	9
0930-23-9-69	69	6	10	4	2	0.2	0.0111	47	737	6	4	18	12	8	6
1321-23-9-69	70	6	10	4	2	0.2	0.0111	55	737	6	6	22	16	11	9
1522-23-9-69	71	6	10	4	2	0.2	0.0111	68	737	6	5	20	13	10	7
										Maximum		34	29	27	26
										Minimum		18	12	8	5
										Average		23	18	13	10
										Spread		16	17	19	21

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27 Abstract

Restoration of quality to polluted lakes by inflows of clean water with simultaneous outflow of polluted water was investigated. Elliptical basins were used in the laboratory to simulate shallow lakes. The investigation determined the influence of selected geometric and flow parameters on the flushing efficiency.

The theoretical analyses are combined with the experimental results to obtain equations for predicting the flushing curves. Application of these equations will give the potential flushing efficiency of a proposed flushing scheme.

The width of the basin perpendicular to the axis of flow is an important parameter. In general, narrower basins have better flushing action and less erratic flow patterns than wider basins. The pollution remaining in a basin after any interval of flushing is primarily dependent on the time of the flushing interval divided by the detention time of the basin.

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